

Circumstellar disks during various evolutionary stages

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Abstract. Disks are ubiquitous in stellar astronomy, and play a crucial role in the formation and evolution of stars. In this contribution we present an overview of the most recent results, with emphasis on high spatial and spectral resolution. We will start with a general discussion on direct versus indirect detection of disks, and then traverse the HR diagram starting with the pre-Main Sequence and ending with evolved stars.

1. Introduction

Disks and disk-like structures are ubiquitous in astrophysics, they can be found at small scales as rings around planets in our Solar System, which in turn were formed in a disk surrounding the young Sun. At much larger scales we find the accretion disks around the central Black Holes that power Active Galactic Nuclei, while larger still, we know of course of disk galaxies. From a stellar evolution point of view, they provide crucial information about the formation of stars, as these grow via the accretion through a disk. At later stages the disk-like structures are associated with the shaping of the ejecta of evolved stars, such as the beautiful Planetary Nebulae and probably also the rings seen around SN1987A.

The *direct* detection of circumstellar disks has always been a challenge. Particularly so for the inner parts where all the action happens. Not surprisingly, this is because most of the emission comes from the inner disks. To give an idea of the scales involved, for example the bulk of the ionized gas that gives rise to hydrogen recombination lines is often confined to distances of order several stellar radii from the star. Up until the turn of the century, we mostly had to rely on indirect techniques to study this material, and it is only very recently that we have been able to spatially resolve such disks on a more-or-less routine basis.

Historically, spectroscopy has been a powerful diagnostic for the presence of disks. As far back as the thirties, in a seminal paper Struve (1931) not only hypothesized that the doubly peaked $H\alpha$ recombination emission lines observed towards bright Be stars originated from a rotating disk, he also backed this up with model simulations. This comparison of data with models is a very early application of an approach of which we will see many examples during this workshop. Although very compelling, Struve's disk hypothesis suffered from the fact that the spectroscopy can not provide *direct* evidence for a disk. The quest to prove once and for all that Be stars are surrounded by disks has taken several decades. We should not omit the important contribution of spectropolarimetry in this quest. As explained in much more detail by Magalhães in these

proceedings, spectropolarimetry is a very powerful method to probe circumstellar material close to a star. It takes advantage of the fact that due to collisions with electrons in an ionized medium, the light from the star is much more polarized than the emission lines such as $H\alpha$ which originate from the gas itself. As only non-round geometries will result in a net polarization, the difference in polarization levels over $H\alpha$ and the continuum serve as excellent diagnostics of very small scale disks. Poeckert & Marlborough (1977) refined this technique and computed the polarization signatures from rotating disks. In a series of papers, they applied this method to Be stars and demonstrated that disks are the best explanation for the observations. The final chapter in this story is the interferometric image of the Be star ζ Tau, taken in a narrow band $H\alpha$ filter presented by Quirrenbach et al. (1994). The elongated structure clearly reveals the presence of a disk, with a position angle on the sky consistent with the polarimetry. This paved the way for further detailed studies and it has now even become possible to both spatially and spectrally probe the disks and their kinematics. For example, very recently it could be determined that the disks rotate Keplerian (Wheelwright et al. 2012a; Kraus et al. 2012), using spectro-astrometry and VLTI interferometry respectively. This finding allows us to move forward and investigate the disk origins with much better observational constraints. I will refrain from reporting on more recent work on Be stars as these are covered in many other contributions in these proceedings.

This historical note also tells us the importance of Be stars in the grander scheme. Due to their brightness and proximity, many new observational techniques, including those mentioned above, are tried and tested first on the bright and nearby Be stars. Later, when the detection techniques have improved, often in combination with larger telescopes, the methods can then be applied to other types of object. It should also be noted that the direct confirmation of a disk by interferometry validates indirect methods such as the spectroscopy and polarimetry as viable disk diagnostics. We should of course keep in mind that there still remain caveats that are inevitably associated with indirect methods. Spectroscopy for example can often be interpreted in many ways, while even rotating disks do not necessarily display doubly peaked lines (e.g. Elitzur et al. 2012).

With the exception of the Be stars, it is fair to say that at the turn of this century, most evidence and information derived for circumstellar disks concerned indirect methods. Since then, we have seen a wealth of new methods to detect and study disks in detail. These include spectro-astrometry (e.g. Wheelwright, these proceedings), optical/NIR interferometry (Stee, Groh, Millour all in these proceedings) and integral field spectroscopy (Stecklum, these proceedings). Last but not least, a significant development is the increased interplay with highly sophisticated models to interpret these data (Bjorkman, Carciofi, Jones, these proceedings).

In the following, I highlight several examples of disks and disk-like structures around stars at various stages of their evolution. I will concentrate on high resolution studies in the top of the HR diagram, which contains both young and evolved objects. I tried to avoid too much overlap with other presentations at this meeting. Even so, given the space constraints, it will be a necessarily shallow tour, which by no means can be regarded as complete, and much good work may not be cited. The citations that are given should serve as a good start in any search for relevant references. Also, the review may seem optically/NIR biased, this is simply because at present the inner parts of the disks are most efficiently traced by diagnostics at the shorter wavelengths.

I should finish this introduction with a cautionary remark. Any high-resolution observation, be it spatial, spectral or temporal, is very time consuming. The papers describing the state-of-the-art are therefore often necessarily single-object papers. It is tempting to extrapolate the conclusions reached for individual objects to the general class. Instead, this is the best opportunity to use these detailed studies to support the indirect diagnostics for which much larger samples are available so that more robust general conclusions can be drawn.

2. Where it starts, the pre-Main Sequence

The ambiguity associated with indirect methods is well illustrated by the lively debate in the nineties about the nature of the circumstellar material around the intermediate mass pre-Main Sequence Herbig Ae/Be stars. The debate concerned whether Herbig Ae/Be stars were surrounded by disks or not (see e.g. Waters & Waelkens 1998 for an overview at that time). The question was relevant as the formation of massive stars was, and in many ways still is, a matter of uncertainty. A key difference with the formation of lower mass, Sun-like stars, is that the lower mass stars sustain magnetic fields, and grow via magnetically controlled accretion through a disk. On the other hand, higher mass stars with radiative envelopes are not expected to form in this manner. To make matters worse, a spherical accretion geometry has its own difficulties as strong radiation pressure from these hotter stars may halt accretion altogether. Recently Krumholz et al. (2009) were able to show from high resolution computations that massive stars can indeed form by disk accretion. The outflows are channeled through the bipolar cavity and consequently the disk undergoes less radiation pressure. A side result of their calculations is that due to fragmentation of the original disk structure, massive stars are predominately formed in roughly equal mass binaries at separations of order au. A prediction which we come back to later.

Observationally, the study of massive young stars is, amongst others, hampered by the fact that they are much rarer than lower mass stars, and therefore much further away, requiring high resolution studies to probe the accretion region. However, imaging of these objects was not possible for a long time, and astronomers resorted to the next best diagnostic, the Spectral Energy Distribution (SED). The trouble however is that fits of SEDs are degenerate. They can be readily explained by both disks and spherical envelopes, with either possibilities having had their own proponents (e.g. Pezzuto et al. 1997). Headway was only made when Mannings & Sargent (1997) detected rotating disk-like structures around some Herbig stars, and the presence of disks was seemingly established. Not much later, Miroshnichenko et al. (1999) unified both SED scenarios by demonstrating that the simultaneous presence of both components can explain the SED; the inner, warm, disk contributes to the NIR excess, while a cooler spherical envelope dominates the longer wavelength excess emission. The case of disk accretion for Herbig Ae/Be was not yet settled however, as the larger (200-600 au) disk-like structures observed at mm wavelengths are too far from the star to probe accretion. Interestingly, the issue that many such disk tracers only probe regions far out and thus can not be used to study the accretion process is often overlooked.

The most significant progress in this field over the last years is that optical/infrared interferometric instrumentation made observations of the inner disks at milli-arcsecond scales possible. This is at scales orders of magnitude smaller than the outer disks detected by infrared and (sub-)mm observations. The inner disks were first observed us-

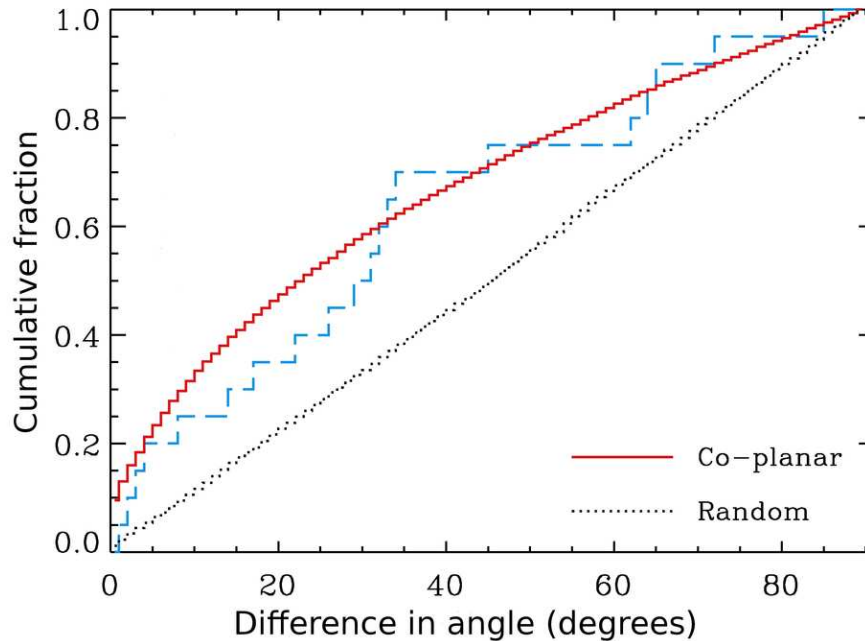


Figure 1. This figure shows the cumulative fraction of the difference between the disk polarization angles and the binary PAs of a sample of Herbig stars (blue dashed). When the angle is 90° , the orbit and disk have the same position angle on the sky. If both are aligned (i.e. co-planar), a distribution as presented by the red solid line would be observed (due to, amongst others, inclination effects, not every co-planar system would have a disk and orbit with the same observed PA). The black dotted line represents the distribution if the two angles were randomly distributed. The co-planar scenario is the most likely situation, lending support to the disk-fragmentation scenario by Krumholz and collaborators (Wheelwright et al. 2011, see text).

ing single baselines which allowed basic size measurements. It was found that the inner boundaries of the disks get larger as a function of luminosity, consistent with the notion that the dust sublimation radius is measured (as documented by e.g. Millan-Gabet et al. 2007). However, not all Herbig Ae/Be stars follow this relationship, and some objects turned out to be smaller than predicted. This has led to several suggestions for the nature of the near-infrared emission. Competing ideas include that the near-infrared emission comes from optically thick gas (Kraus et al. 2008), or that it is due to refractory grains which can survive higher temperatures (Benisty et al. 2010). Full model-independent images of several Herbig Ae/Be stars have now been published, proving beyond doubt that the objects are surrounded by disks (e.g. Benisty et al. 2011 and references therein). The number of imaged objects is still limited. Improved sensitivity and instruments that can combine more baselines such as those on CHARA, MROI and VLTI are either just installed and planned respectively, making it much easier to obtain images and paving the way for statistical studies. In parallel, the next step is to fully understand and parametrize the properties of the disks in order to follow the formation and evolution of intermediate and massive stars. An early example has been published by Weigelt et al. (2011) who took advantage of the high spectral resolving power of

VLTI/AMBER ($R \sim 12000$) and spectrally resolved the $\text{Br}\gamma$ line of the Herbig Be star MWC 297. By fitting the spectral line, they find that the emission is due to a disk-wind.

Furthermore, returning to the point originally made about sample sizes, informed by the fact that the Herbig Ae/Be stars are surrounded by disks, Wheelwright et al. (2011) use their large sample of objects with spectropolarimetric data which trace the disks and apply it to the (many) known binaries in the class. They find that the disks around the primary objects are aligned with the orbital planes of the binaries (see Figure 1). Most Herbig Ae/Be stars are found in binary systems with separations of order au's, while their mass ratios peak at unity (Wheelwright et al. 2010). With the new finding that the orbital planes and the disks are aligned, the prediction by Krumholz et al. (2009) that the disk fragmentation leads to binaries with the same properties as now observed, is confirmed.

Finally, there are the more embedded Massive Young Stellar Objects with masses exceeding $10\text{--}15M_{\odot}$, these are on average even further away than Herbig Ae/Be stars, with as added complication that they are optically invisible due to the large extinction. De Wit (these proceedings; de Wit et al. 2011) presents tantalizing evidence for disks around these most massive young stars as well.

3. Moving on, to the Main Sequence

The disks concerned in the previous section are the accretion disks which formed as a result from the collapse of a rotating cloud. After the accretion has halted, and the star is settling onto the Main Sequence, the disks gradually disappear, mostly due to photo-evaporation. During this phase, the disks are commonly referred to as proto-planetary or transition disks. Later, after most dusty particles should have been lost due to processes such as the Poynting-Robertson effect and radiation pressure, the remaining “debris” disk's dust reservoir is replenished by collisions of larger bodies. Before the disks have disappeared altogether, planets must have formed.

The transition disks are the birth places and thus important laboratories to study the formation of planets. Evidence that planets are indeed present in these disks has emerged over the past decade. Early SEDs of Herbig Ae/Be stars and their evolutionary successors were found to display both a hot and a cool component suggesting the presence of a single disk with a gap in which the dust had been cleared (Malfait et al. 1998). These gaps were confirmed by high resolution observations at sub-mm and mm wavelengths (for an overview see the paper by Williams & Cieza 2011), however they are located relatively far from the star by virtue of the sub-arcsecond resolution of the data. The inner au's were probed by spectro-astrometry (Pontoppidan et al. 2008), while optical interferometry revealed a hole in the disk around HD 100546 at a distance of less than 10 au from the star (Tatulli et al. 2011).

Such gaps are now widely accepted as being due to a giant planet orbiting the star. This was basically confirmed since planets have been found around objects with disks. For example, β Pic and Fomalhaut both have a proto-planetary disk and host a planet (Lagrange et al. 2010; Kalas et al. 2008), while T Cha has recently been reported to have a planet located in the gap itself (Kraus & Ireland 2012). Despite these successes, it is very hard to detect planets around active objects surrounded by circumstellar material. The holes in the disks as indicated by the SEDs can be used as a proxy for the existence of planets around these stars. The ensuing statistics may tell us a great deal about the timescales involved in the formation of planets. Ironically, a current line of

research investigates whether the planets themselves play a dominant role in the disk dispersal.

Other disks around Main Sequence stars are known, such as those around the Be stars. These are not "primordial" remnant accretion disks anymore, instead, their origin must be found at the Main Sequence. Their formation mechanism is however not well understood, and an active community works on the topic. The Be stars will be covered by many in these proceedings (see Stee for a review on observations, Bjorkman and Jones on theory in these proceedings).

4. The later stages, the post-Main Sequence

The circumstellar material that is found in the post-Main Sequence phase is due to mass loss from the star. The circumstellar matter can be found in many shapes, ranging from spherical shells to disk, axi-symmetric, structures. The latter are most likely responsible for the shaping of the Planetary Nebulae (PN), while rapidly rotating stars are now predicted to be Gamma-Ray Burst progenitors and the mass loss of such objects will be primarily concentrated in the equatorial plane.

Entire conferences have been dedicated to the aspherical PNe (Zijlstra et al. 2011). Whereas their progenitors, the AGB stars are mostly round on larger scales, the PNe show a wide range of, mostly, axi-symmetric morphologies ranging from nearly round elliptical nebulae to highly collimated bipolar jet-like geometries. The search is on for the origin for the change in geometry as the stars evolve from the AGB to the post-AGB to the PN stage (van Hoof et al. 1997). This may have its foundations in the clumpy winds that have been seen at very small scales in the AGB phase (Weigelt et al. 2002). The subsequent phase in evolution is when the objects are post-AGB stars. These objects have long been inferred to be surrounded by disks based on indirect evidence such as their SEDs (e.g. de Ruyter et al. 2006). Direct evidence for disks with inner radii of order 10 au has recently come from interferometric measurements (Deroo et al. 2007; Lykou et al. 2011). There seems to be a strong correlation of the presence of bipolar PNe with binarity. The objects which have direct evidence for disks in the papers mentioned above are no exception, as they are also located in binary systems.

The situation for higher mass is more unclear. There is a diverse selection of, often very variable, objects to be found in the upper regions of the HR diagram, and even their evolutionary connections are not always clear. A crude evolutionary scenario for objects around the $25\text{-}40M_{\odot}$ mass can be summarized as the following

O star \rightarrow (Red Supergiant) \rightarrow Yellow Hypergiant/post-Red Supergiant \rightarrow Luminous
Blue Variable/B[e] \rightarrow Wolf-Rayet \rightarrow Supernova

Members of most of these evolutionary groups are plotted in the HR-diagram in Figure 2. The various phases occupy complementary parts in the diagram and define a more-or-less well defined sequence.

The Red Supergiants entry in the sequence above is put between brackets, as these stars have not been observed and are not expected at the highest masses. The Yellow Hypergiants which are (obviously) located bluewards of the RSG branch can be either pre- or post-RSG, explaining why the extra qualification post-RSG is added in the evolutionary sequence. I also took the liberty to add the B[e] supergiants, which,

surprisingly perhaps, are not often explicitly mentioned in evolutionary schemes such as this one. Their location in the HR diagram is however well established for the Magellanic Cloud sources (Zickgraf et al. 1986), and with more than 10 known, they are as numerous as the LBVs in the Magellanic Clouds too. If not the direct descendants of the LBVs as Figure 2 might suggest, the B[e] supergiants are conceivably in a similar stage of their evolution.

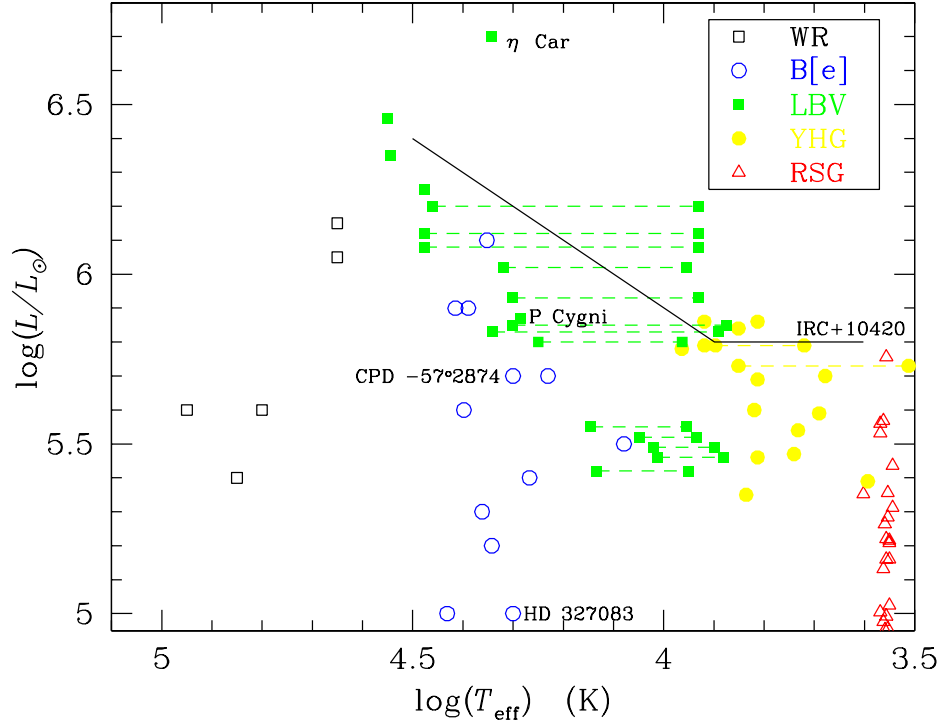


Figure 2. Updated version of the HR-diagram from Oudmaijer et al. (2009), with some data taken from Smith et al. (2004). Shown are both Galactic and Magellanic Cloud Luminous Blue Variables (LBV), Yellow Hypergiants (YHG) and Red Supergiants (RSG). Added to the Galactic B[e] objects mentioned in the text, are the Magellanic Cloud B[e] supergiants with their data taken from Zickgraf (2006), the WN/WR stars mentioned in Vink et al. (2011) whose parameters are taken from Hamann et al. (2006). Objects which are mentioned in the text are indicated with their name. The solid line denotes the Humphreys-Davidson limit.

Let us discuss what we know about disks around the objects in their evolutionary order. A more general overview of the circumstellar material around massive evolved stars can be found in Smith (2011). Direct evidence for disks around O stars is cur-

rently lacking, no interferometric imaging studies have yet reported any. The Oe stars and variants on their spectral types, have emission lines whose appearance suggest the presence of disks in the same manner as for the Be stars. Having said that, spectropolarimetric studies do not yield any detections of line-effect and thus do not provide evidence for disks based on spectropolarimetry (see Vink et al. 2009 and references therein). However, we should bear in mind that this absence of evidence for disks should not be taken as evidence for the absence of the disks, so the question of disks around O stars is still open. Moving to the Red Supergiants, despite some of these being amongst the largest stars on the sky, disks have not been observed. Diffraction limited (AO-assisted) imaging of objects such as Betelgeuse and μ Cep reveal complex and clumpy environments (Kervella et al. 2011; de Wit et al. 2008a). These could be the result of mass loss which is possibly linked to the large spots on their stellar surfaces. These stars are large enough that interferometric studies have been mostly used to map the surfaces of these huge stars (Ohnaka et al. 2011).

Direct information on the inner part of the circumstellar material around the post-Red Supergiants is also sparse. The best known member of the class, IRC +10420, has been the subject of several VLT/AMBER studies, (de Wit et al. 2008b; Driebe et al. 2009). The lack of baselines in the former did not allow an unambiguous determination of the geometry, while the fact that a spherically symmetric radiative transfer model did not fit the data, led the latter to conclude that the inner parts are a-spherical. We recently obtained new data and compiled all data available to re-visit the issue (Oudmaijer & de Wit 2013). The number of baselines and baseline coverage is arguably the best that can be achieved for this equatorial target. Of particular note is that the differential phases across the Br γ emission line can be best explained by the fact that across the line, the second lobes of the visibilities are probed, giving a characteristic flip in phase angle. This allows a better handle on the geometries involved. The best analytic model that can reproduce the data is a two ring model, reminiscent of the rings observed towards SN1987A, with a small circumstellar disk which blocks the light from the receding ring. Ironically, although the optical interferometry discussed here can provide direct evidence for disks, in this particular case, its evidence is mostly indirect.

Moving on to the LBVs, Groh (these proceedings) discusses the innermost regions of η Car, and finds that the geometry can be best described as a torus-like structure - as opposed to a disk which for the purposes of this review can be best defined here as a structure whose scaleheight at a given radius is (much) smaller than the radius. It is not obvious whether the binary companion of η Car has anything to do with the mass loss in the equatorial regions however. When considering the other LBVs, no evidence for disks has been published. Interferometry of the H α line of P Cygni (a very rare type of observation), resulted in a round picture (Balan et al. 2010). Indirectly, most objects show signatures in their spectropolarimetry similar to those in Be stars. Repeat observations showed that the polarimetric signatures are not consistent with the disk hypothesis however; the spectropolarimetric variability indicates the ejection of clumpy material in random directions instead (Davies et al. 2005).

So, are any evolved stars associated with circumstellar disks? The best candidates would seem to be the B[e] supergiants. The B[e] stars in the Magellanic Clouds have long been suggested to be surrounded by disks based on their hybrid spectral appearance. Broad emission and absorption lines can be identified with a fast polar wind, while lower excitation and narrower lines find their origin in a disk

(Zickgraf et al. 1985), consistent with spectropolarimetry (Magalhães et al. 2006). The objects are thought to be very rapid rotators, which may explain the preponderance of disks amongst them. Unfortunately, the distance to the Magellanic Clouds is prohibitive for detailed disk studies and we have to resort to the B[e] stars' galactic cousins, which happen to constitute a diverse collection of objects. The identification is particularly cumbersome as the distances, and thus bolometric luminosities of the objects are hard to come by, hampering the usual distinction between young and evolved stars. In addition, it turns out that a wide variety of objects can adhere to the primary classification criterion of B[e] stars, namely the presence of forbidden emission lines (Miroshnichenko 2007). Several of the galactic B[e] supergiants have now been observed in interferometry. Domiciano de Souza et al. (2007) describe the particularly compelling case of CPD -57°2874, where both AMBER interferometry tracing the Br γ emission and hot dust continuum and MIDI interferometry tracing warmer dust reveal a disk. Other detailed studies show a different picture, and seem to converge on the idea that a substantial number of the accepted Galactic B[e] supergiants are members of binaries (HD 327803, Wheelwright et al. 2012b; HD 87643, Millour et al. 2009). It is intriguing that the only massive evolved stars with evidence for disks are often members of binary systems.

We finish this quick tour of the HR diagram with the Wolf-Rayet stars. They are on average too faint yet to be systematically probed by interferometry. Larger scale clumpy, round winds have been observed. Closer in, the evidence for deviations from spherically symmetry is sparse. Indeed, although no disks have been directly observed towards the WR-stars at present, indirect evidence for disk-like structures has been used to strengthen their status as GRB progenitors. Harries et al. (1998) find a minority of WR stars to exhibit spectropolarimetric signatures indicating deviations from spherical symmetry. Vink et al. (2011) used this fact to hypothesize that these objects can be the elusive rapidly rotating stars that are suggested to be the GRB-progenitors. Normally, rotation rates of WR stars are difficult to measure because of their strong line emission, but an equatorial wind can be best explained by rapid rotation. They went further and note the fact that this WR-subsample are associated with ejection nebulae from the previous RSG/LBV phase (as found by comparing with the sample of Stock & Barlow 2010). Older WR stars will have spun down and their ejection nebulae would be long dispersed in to the interstellar medium, and be invisible. In other words, the objects presented by Vink et al. (2011) are young, rapidly rotating, WR stars, and among the strongest GRB-progenitor candidates.

To conclude this section. It would seem that disks such as clearly observed around young stars are not present in the same abundance or as clear in the post-Main Sequence phase of evolution. Clumpy material and binarity play a large role, and often flattened structures are associated with the binaries. The objects with the strongest - yet still indirect - evidence for disks, the B[e] supergiants are thought to be rapid rotators, and when linking this with the current thoughts on GRBs, can be a serious contender for their progenitors.

5. Final Word

This overview presented some of the latest results in high resolution studies of disks in various evolutionary phases. By the turn of the century, we had to rely mostly on indirect evidence for the presence of small scale disks around objects. The most compelling

observations at that time were limited to the bright and nearby Be stars. As a result these objects acted as the pathfinder, not only then, but also now in ever more refined disk studies. We found that with the advances in optical/infrared interferometry, spectro-astrometry, IFU spectroscopy often combined with routine AO support, *direct* evidence for disks has come forward in abundance this century. The next steps will be to put the samples on a more statistical footing, and derive astrophysical parameters for them to finally and fully understand what is happening. The leaps in both observational techniques and theoretical and numerical models to interpret those new data over the past decade are remarkable and promise an exciting future.

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